

SUMMARY OF IONIZING RADIATION ANALYSIS
ON THE LONG DURATION EXPOSURE FACILITY

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ABSTRACT

The ionizing radiation measurements flown on the LDEF were contained in 15 experiments which utilized passive detectors to pursue objectives in astrophysics and to measure the radiation environment and dosimetric quantities. The spacecraft structure became sufficiently radioactive to permit additional important studies. The induced activity allows extensive radiation mapping in the structure, an independent comparison with experiment dosimetric techniques, and significant studies of secondary effects. The long exposure time, attitude stability, and number and types of measurements produced a unique and critical set of data for low Earth orbit that will not be duplicated for more than a decade. The data allows an unprecedented test, and improvement if required, of models of the radiation environment and the radiation transport methods that are used to calculate the internal radiation and its effects in spacecraft. Results of measurements in the experiments, as well as from radioactivity in the structure, have clearly shown effects from the directional properties of the radiation environment, and progress has been made in the dosimetric mapping of LDEF. These measurements have already influenced some Space Station Freedom design requirements. Preliminary results from experiments, reported at this symposium and in earlier papers, show that the 5.8 years exposure considerably enhanced the scientific return of the radiation measurements. The early results give confidence that the experiments will make significant advances in the knowledge of ultraheavy cosmic rays, anomalous cosmic rays, and heavy ions trapped in the radiation belts. Unexpected phenomena have been observed, which require explanation. These include stopping iron group ions between the energy ranges anticipated for anomalous and galactic cosmic rays in the LDEF orbit. A surprising concentration of the ^7Be nuclide was discovered on the "front" surface of LDEF, apparently transported up from the stratosphere with exceptional efficiency. LDEF will clearly be a landmark mission in astrophysics and in the study of the radiation environment in LEO.

INTRODUCTION

The Long Duration Exposure Facility (LDEF) carried 9 experiments designed to study particular aspects of the ionizing radiation encountered during the mission. Six more experiments included detectors for radiation monitoring. In addition, the spacecraft structure and experiment materials acquired a low (~1 to ~100 pico Curies per kg) level of radioactivity. The distribution of the induced radionuclides in samples of the LDEF structure, measured in sensitive gamma ray spectroscopy facilities, allows significant additional studies of the radiation environment and its interaction with the spacecraft.

The radiation measurements on LDEF are listed in Table 1. Three experiments (A0178, M0001, M0002-2) (refs. 1,2,3,4) were designed to measure the composition and spectra of galactic or "anomalous" cosmic rays. M0002-2 also studied heavy ions trapped in the Earth's magnetic field. Experiment M0002-1 (ref. 1) had multiple detectors at different locations to measure the trapped proton

fluence, energy spectra and directional characteristics. Experiments P0006, P0004, M0004, and A0015 (refs. 1,5,6,7,8,9,10) contained a variety of passive detectors to measure the radiation dose, heavy particle fluence, linear energy transfer (LET) spectra, and several aspects of the secondary radiations including neutrons and the concentration of heavily ionizing recoil nuclei. These experiments contained detectors at various shielding depths typically encountered in manned spacecraft. The experiments are described further in NASA SP 473 (ref. 1), papers of this symposium, and the referenced experiment reports. Table 1 summarizes the radiation measurements and lists the detector types and principal measurement categories in each.

The cosmic ray experiments address fundamental questions about the nucleosynthesis of heavy elements in the galaxy, and acceleration of the nuclei to high energies. A0178 measured the elemental abundances of galactic cosmic rays above atomic number 65. It will make the most significant study yet of the actinides (eg. thorium, uranium) in the cosmic rays, and will define their abundance relative to lighter elements (eg., platinum, lead). This data will reveal the importance of rapid (explosive) nucleosynthesis for heavy element production in the galaxy. M0001 was designed to study both galactic and anomalous cosmic rays. The low energy "anomalous" nuclei are now thought to be from the interstellar gas which enters the solar system, becomes partially ionized, and is then accelerated (by shock waves) up to a few tens of MeV. These particles carry information about the interstellar medium and particle acceleration in the solar system. In addition to anomalous cosmic rays, experiment M0002-2 also studied low energy heavy ions that are trapped in the inner radiation belt. The trapping mechanism for these particles is not understood.

Experiments P0006, P0004, A0015, and M0004 contained a variety of passive detectors to measure absorbed dose, particle fluences, linear energy transfer spectra, and neutrons. The P0004 detectors were distributed at various depths in the seeds experiments (P0004-1,2)(ref. 1). A0015 carried many detectors to characterize the radiation exposure of biological samples. Some of these detectors were used to locate heavy nucleus tracks which passed through the biological samples. P0006 comprised a comprehensive set of dosimetric detectors at precisely defined shielding depths in the seeds experiments tray. Experiments M0003, M0006, and A0138-7 (ref. 1) also carried detectors for local radiation dose monitoring.

A set of 5 metal samples (Co, Ni, Ta, V, In) (ref. 11) of approximately 100 gm each were placed in 5 separate locations around LDEF. The metals were selected for specific activation products and cross-sections to study the activation process and to measure the flux of the activating particles (trapped protons, cosmic rays, and neutrons). The flux and spectra of neutrons, which have not been frequently nor definitively measured in spacecraft, can be studied through activation reactions which are exclusively, or partially, caused by neutrons.

In addition to the activation detectors intentionally placed on LDEF, the 5.8 years of exposure caused the radioactivity induced by trapped protons and cosmic rays in aluminum, stainless steel, titanium, lead, and other metals of the spacecraft structure to reach significant levels (11,12,13,14,15). Although the activity was small (~1 to ~100 pico Curies/kg), it was readily measured with high resolution gamma ray spectrometers. The initial activation measurements were made of the full spacecraft (between 2 weeks and 2 months of LDEF recovery) with a cooled germanium detector array (ref. 16) at Kennedy Space Center. Subsequently, about 400 samples of the metal structure of LDEF (and some experiment samples) have been measured in shielded low background spectrometers at nine laboratories (refs. 17,18,19,20). The activation data set is an important complement to dosimetry measurements performed in experiments. It forms a complete dosimetric map of LDEF, filling in gaps where other experiment data do not exist, and gives a measurement independent from other dosimetric techniques (e.g., thermoluminescent dosimeter (TLD) dose), which could be subject to different errors. This data set will be a

definitive benchmark for methods that are used to calculate activation in space.

The set of passive radiation measurements on LDEF is the most comprehensive yet flown on low Earth orbit missions. The value of these measurements is enhanced by the spacecraft's Earth-fixed flight attitude (which is the same for SSF). This allows the directional characteristics of the ambient radiation (refs. 21,22,23,14), and its effects at various shielding depths, to be studied. The large number and variety of measurements at various locations and shielding depths, the orbit, the attitude stability, and the long duration make this a valuable and unique data set for studies of the LEO radiation environment.

RADIATION ENVIRONMENT PREDICTIONS

Predictions of characteristics of the radiation environment and its effects, such as absorbed dose, in LEO have been generally accepted as accurate to a factor of ~2, but predictions with different codes and assumptions have often differed by a larger factor. Single event upset predictions can differ among methods by a factor of 10. Secondary radiations such as neutrons and recoil nuclei have been difficult to measure on spacecraft. Measurements of the secondaries are scarce and corresponding predictions are more rare. Furthermore, the directional characteristics of the trapped proton flux have been previously ignored in predictions of effects, and for spacecraft stabilized like LDEF in 28.5° orbits, this causes a variation in magnitude of 2-3, which is strongly dependent on location in the spacecraft. The present uncertainties in radiation prediction would lead to significant impacts in a number of future programs. For long duration missions such as the Space Station and AXAF, uncertainties in predictions can lead to increased costs in electronic parts, or unfavorable trade-offs between manned mission duration and orbital decay rates, or uncertainty in degradation and replacement cycle of observatory instruments. The LDEF radiation data will considerably improve prediction methods for resolution of these kinds of issues.

IONIZING RADIATION SPECIAL INVESTIGATION GROUP

The LDEF Special Investigation Groups (SIG's) (Materials, Meteoroid and Debris, Systems, Ionizing Radiation) were chartered to perform measurements and analyses that were not a part of the LDEF experiments objectives but are important for application to future missions. The SIG's must ensure that relevant and applicable information for design and development of future missions is reported and archived, and that the results will be in a form useful to those programs. Each SIG defined specific objectives toward these general goals, in accord with programmatic constraints. The main elements of the Ionizing Radiation Special Investigation Group (IRSIG) operating plan are shown in Figure 1.

The IRSIG has concentrated its efforts in the following areas:

1. Pre-recovery predictions of radiation dose, particle fluences, LET spectra and radioactivity (refs. 11,12,13,22,24).
2. A post-recovery radiation safety inspection. This inspection was performed soon after Columbia's payload bay doors were opened in the Orbiter Processing Facility (OPF) with hand-held survey detectors, and dry wipes of small areas. No radioactivity enhancements above background were detected with the survey instruments. KSC personnel performed these surveys.

3. A full spacecraft activation measurement. This measurement was performed for two months in the SAEF II building, while experiment trays were removed, with a very sensitive germanium spectrometer array (ref. 11,16).

4. A program was organized to measure the induced activity in about 400 samples of the spacecraft structure and experiments materials selected at many locations and shielding depths (refs. 11,14,15). The activation measurement data set provides an excellent test of calculational methods such as the directional trapped proton environment model, the High Energy Transport Code (HETC), and other methods to predict activation in spacecraft. Furthermore, the activation measurements and prediction methods are of great interest to the gamma ray astronomy community (e.g., GRO, Mars Orbiter, etc.).

5. Accumulate the radiation data and analysis results from experiments as available, and supply the experimenters with environment calculations and analyses as they become available.

6. Using LDEF data, validate or improve models of the radiation environment and the calculation methods for radiation transport and effects. The environment modeling and calculation program is described in refs. 12,13,14,23,25. The main models and calculations to be applied are the AP8 trapped proton model, AE 8 trapped electron model, a new model for trapped protons which combines AP8 with the directional properties of the protons, methods for calculating induced radioactivity (e.g., the HETC), the cosmic ray environment and methods for calculating linear energy transfer (LET) spectra [e.g., the Cosmic Ray Effects on Microelectronics (CREME) code, and the HETC code]. The definitive application of these methods requires a detailed mass model of the LDEF structure and selected experiment trays, which is currently under development (ref. 25). The principal environments and calculational codes to be employed by the IRSIG are shown in Figure 2 from (ref. 23).

7. The LDEF IRSIG is supporting a number of post-recovery radiation analysis efforts which require accelerator exposures for the calibration of detectors or for the assessment of possible radiation effects. Due to the low altitude and inclination orbit, and the relatively low radiation dose (refs. 22,24), significant radiation effects were not anticipated. Only a few experiments have reported either confirmed or suspected radiation effects.

8. The documentation and archival of data, models, and methods is a major task of the IRSIG. In addition to written reports and summaries of results, the environment models and calculation methods will be documented and placed in accessible networks. The induced activity data and prediction methods will be a major subset of the archive. Activation results (including the occurrence of unusual amounts of nuclides in the original material that have been discovered) will be archived in the Materials and Processes Technical Information System (MAPTIS).

MOST SIGNIFICANT EARLY RESULTS

The early results of the LDEF radiation measurement are covered in subsequent papers of this symposium and in referenced published results. Only a few highlights are listed here.

1. The effects of directional properties of trapped protons have been clearly observed in the following measurements:

a. Absorbed dose from thermoluminescent dosimeters (TLD's) in P0006, P0004, M0004. The West/East ratio is about 2.5 near the LDEF surface (refs. 14,23,26*). Figure 3 illustrates the dose

* unpublished

data along with predictions using the AP8 proton omnidirectional model. These calculations, using two simple shield configurations, show that the omnidirectional proton model cannot match the LDEF data.

b. Induced radioactivity in aluminum tray clamps (^{22}Na gamma ray line) from locations around LDEF (refs. 14,15). Figure 4 displays the ^{22}Na activation data from the tray clamps with a simplified calculation using the proton directional model.

c. The Na^{22} line variation around LDEF observed by the full spacecraft activation measurements (ref. 16).

d. Radioactivity in two stainless steel trunion layers (^{54}Mn gamma ray line) from the leading and trailing sides (refs. 14,15,23).

The analysis of these data (and additional measurements in progress) will provide a high precision test of the new directional model of trapped protons, and the AP8 fluxes.

2. A large body of data has been gathered on induced radioactivity in spacecraft and experiment samples (refs. 14,15) (aluminum, stainless steel, titanium, lead, copper, nickel, etc.). This data set provides a benchmark for calculation methods and environment models. It also is of considerable interest to gamma ray astronomers, whose experiments are sensitive to the background radiation.

A surprising finding was considerable uranium in titanium clamps (in the original material) from the LDEF structure.

Figure 5 is a sample of activation data from small pieces of two stainless steel trunions.

3. Radioactive ^7Be (half life 56 days) was found on the front surface of LDEF on all materials examined (refs. 14,16,27,28), but was absent from the trailing surfaces. Figure 6 shows ^7Be data from the aluminum experiment tray clamps. It is known to be produced by cosmic ray bombardment of the atmosphere with maximum production near ~ 20 km. Its concentration on LDEF is small ($\sim 10^6$ atoms/cm 2), but is about 1000 times the quantity that might be expected from simple atmospheric diffusion. At the symposium several processes that could explain the observation, such as production in the atmosphere by solar flare particles and exceptional transport mechanisms, were speculated. Accelerator mass spectrometry is being employed to search for other atmospheric spallation products (^{10}Be , ^{14}C). ^7Be accommodated to a variety of LDEF surfaces (e.g., aluminum, stainless steel, Teflon).

A recent measurement of ^7Be in the removable surface "oil" film on the Concorde aircraft was reported (ref. 29). Repeated measurements on Concorde will allow the speculated solar flare enhancements of atmospheric ^7Be to be tested.

4. Secondary neutrons and short range recoil nuclei have been measured in P0006 (refs. 5,6). Past measurements of neutrons in spacecraft have been infrequent and subject to large primary particle backgrounds. The LDEF data contain the first statistically significant measurements in space of spectra from high LET recoil nuclei (6). These secondary particles are of importance in determining equivalent dose (biological effects) and the rates of "single-hit" phenomena (e.g., single event upsets (SEUs), sensor noise). The secondary particle measurements are also very important in assessing calculational methods which predict equivalent dose (REM) and high LET particle effects.

5. Radiation Effects: No damaging radiation effects have been reported in LDEF surface materials. This is consistent with the pre-recovery surface dose calculation of $\sim 500,000$ rads from electrons. However, possible radiation effects were reported in uncovered solar cells in experiment A0171 *, the electronics in M0004 (ref. 30), and in quartz crystal resonators (A0189) (ref. 31). Analysis and post-flight testing is continuing.

* Willowby, D. J.; and Whitaker, A. F.: Private Communications.

Genetic damage effects have been observed in experiments containing seeds (P0004-1, P0004-2, A0015) and other biological samples (A0015) (refs. 10,32).

6. Anomalous Cosmic Rays and Ultra-Heavy Cosmic Rays: Three experiments on LDEF were designed to measure rare particles in the cosmic ray flux. These are the low energy "anomalous cosmic rays", and the "ultra heavy cosmic rays" (atomic number above 65). These experiments (M0001, M0002-2, A0178) (refs. 2,3,4) showed results indicating good detector sensitivity and resolution. Only a few percent of the detector material had been processed prior to the symposium. The LDEF measurements are a factor of \geq six more sensitive than any previous measurements, and will be the most sensitive for a decade or more. In addition to astrophysics the anomalous cosmic rays are of interest in single event upset predictions at thin shielding depths (e.g., electronics on the space station truss).

The investigators of M0001 reported stopping iron group ions with incident energies near 600 MeV/nucleon. This is above the energy of anomalous cosmic rays, but below the geomagnetic cut-off for galactic cosmic rays in the LDEF orbit. Their energy range and flux levels suggest they are partially ionized solar energetic particles, but further investigation is required.

7. Heavy ions trapped in Earth's magnetic field: Experiment M0002-2 has measured a small but significant flux of heavy nuclei stopping in the detector and with an angular distribution consistent with trapped belt particles (ref. 4). The trapping mechanism for these particles is yet to be explained.

8. It should be noted that LDEF carried no radiation detectors at sufficiently shallow shielding depths ($< .1$ cm Al) to measure trapped electrons (refs. 22,24). Attempts to measure the electron dose in some surface samples with electron paramagnetic resonance (EPR) techniques are planned.

9. The radiation environment models and transport calculations: Progress has been made in using radiation environment models (refs. 12,13,23) (trapped protons, cosmic rays, earth albedo protons and neutrons), and radiation transport models with simple shield geometries, to estimate various features (such as directional properties) of the radiation, and to guide the emphasis on various measurements (e.g., activation sample priority). A detailed mass model (ref. 25) is under development for use in three-dimensional calculations, which are required for definitive testing of the environments models with LDEF data. Experiments A0178 and M0001 will also make significant use of the mass model in data analyses. The quality of the data reported in these early results indicates that the major objectives of the calculation and analysis program will be met.

The early results presented at this symposium have clearly shown that LDEF will make significant advances in the knowledge of the radiation environment in low Earth orbit (LEO), radiation transport modeling, the biological effects of the space radiation environment, radiation dosimetry, and astrophysics.

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Table 1. The radiation measurements on LDEF.

Radiation Detectors on LDEF

Experiment No.	TLD's ^(a)		PNTD's ^(b)	Activated Materials	Fission Foils	Other Detectors	Main Objective of Radiation Measurement
	Absorbed Dose (rads - Tissue)		Heavy Ion Fluence & LET Spectra	Proton & Neutron Fluence	Neutrons & Spectra	Heavy Ions	
P0004-1 (c)	X		X				Dosimetry
P0004-2 (c)	X		X				Dosimetry
P0006 (c)	X		X	X	X		Environment
M0001 (c)			X	X			Astrophysics
M0002-1 (c)	X		X	X		Microsphere	Environment
M0002-2			X	X			Astrophysics
M0003-12	X						Dosimetry
M0003-17	X						Dosimetry
M0004 (c)	X		X				Dosimetry
M0006	X						Dosimetry
A0015 (c)	X		X		X	AgCl	Environment
A0138-7	X			X			Dosimetry
A0114-1 (c)				X			Effects
A0114-2				X			Effects
A0178			X				Astrophysics
LDEF Structure (c)				X			Effects
No. Detectors							
190		> 500		> 400	22	4	

(a) TLD's = Thermoluminescent Dosimeters

(b) PNTD's = Plastic Nuclear Track Detectors

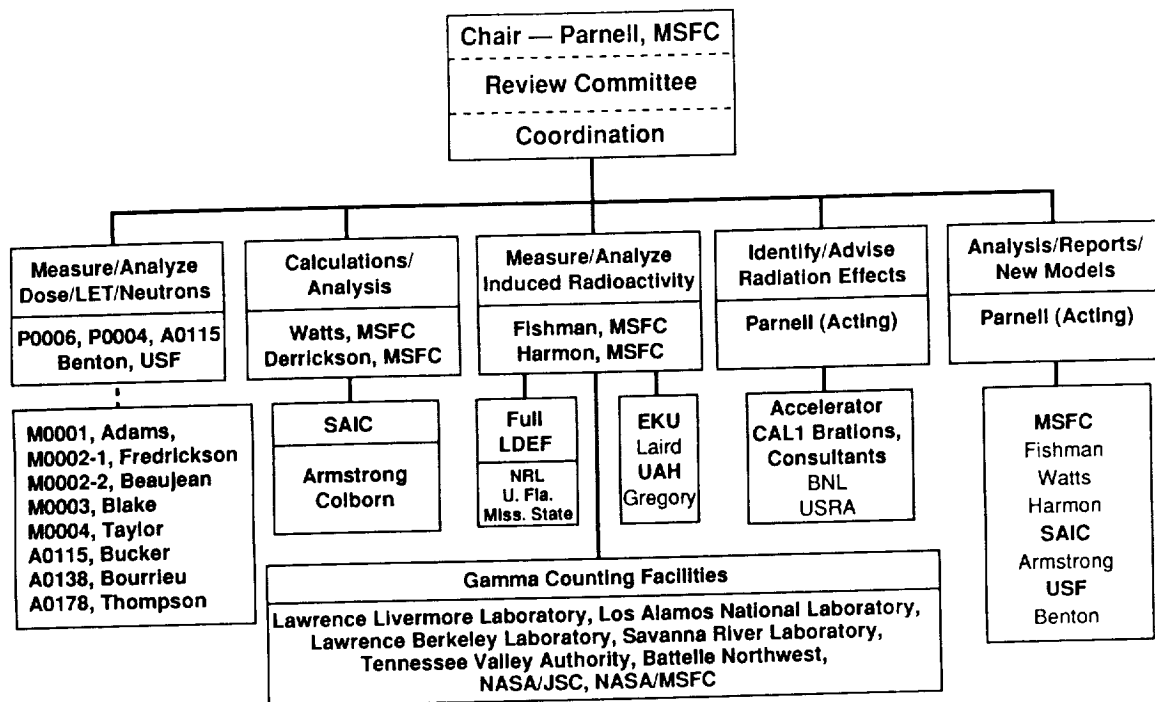


Figure 1. The LDEF Ionizing Radiation Special Investigation Group Functional Organization.

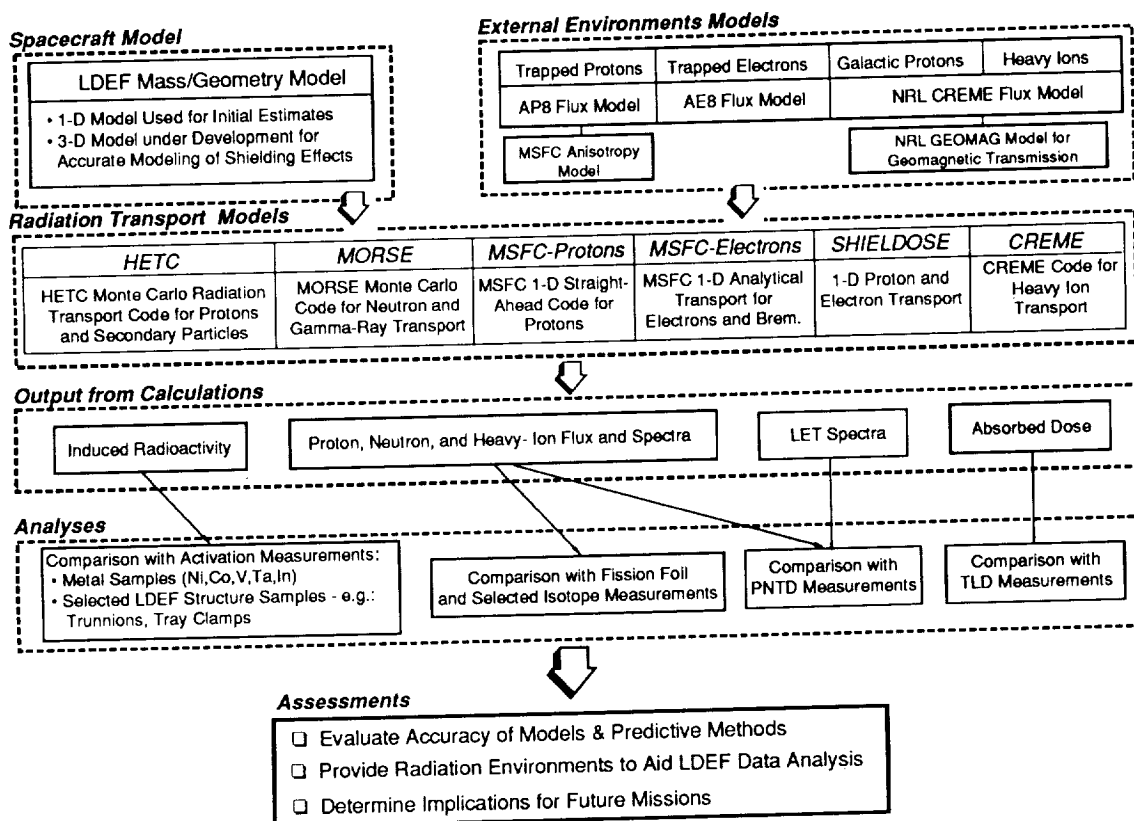


Figure 2. The approach and principal models for the LDEF ionizing radiation calculations (from ref. 23).

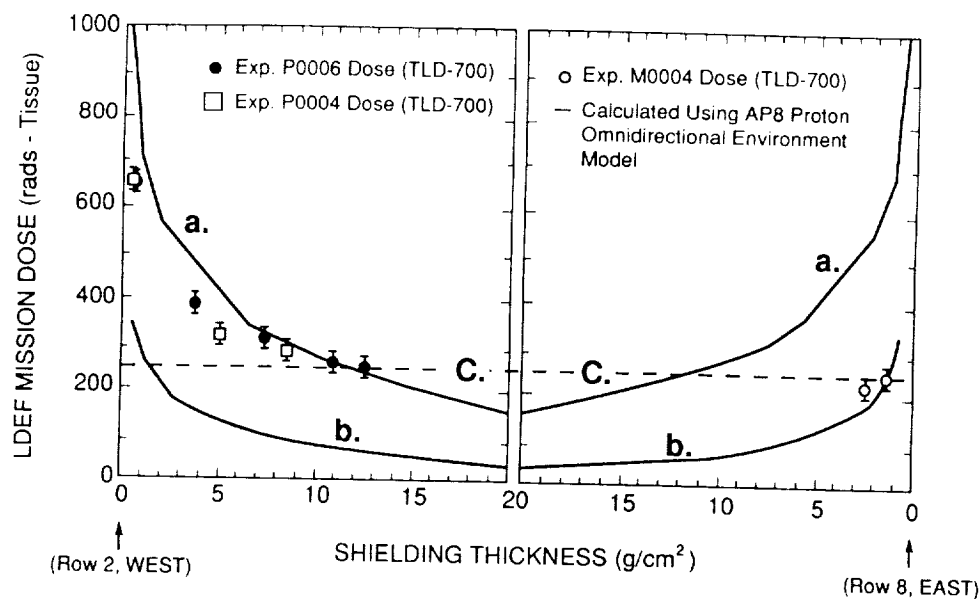


Figure 3. Absorbed dose measurements with thermoluminescent dosimeters (TLD) from three LDEF experiments, with calculations of dose from the AP8 trapped proton omnidirectional model (ref. 22,24,26). Curve A assumes simple spherical shields. Curve B assumes planar (slab) shields. The dotted line indicates the 50 rem annual crew dose limit.

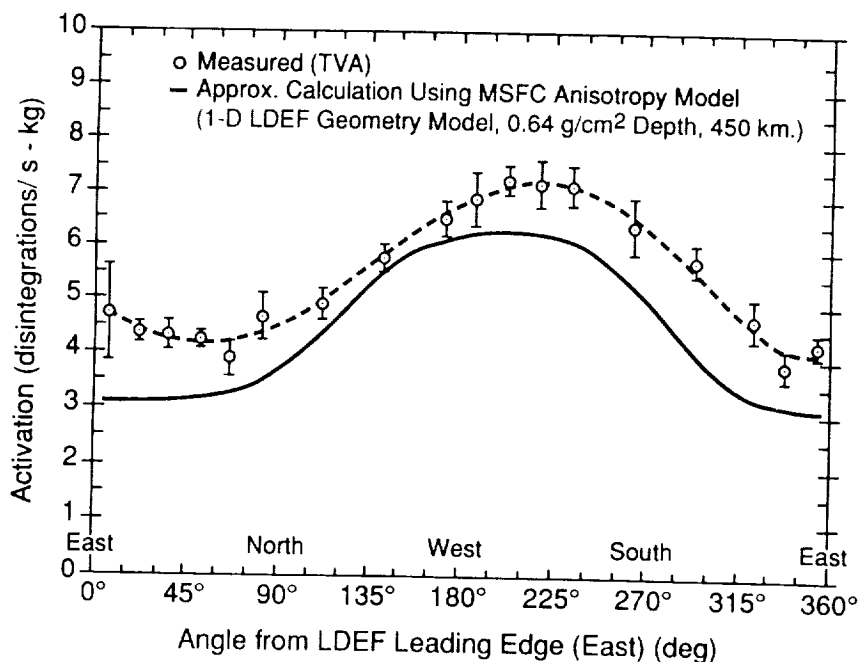


Figure 4. Measurements of the concentration of ^{22}Na in aluminum tray clamps around LDEF. The statistical error bars are due to the short counting time for each sample. The calculation is from a simplified (one-dimensional) planar shield calculation for each data point using a vector proton flux (from ref. 14,15).

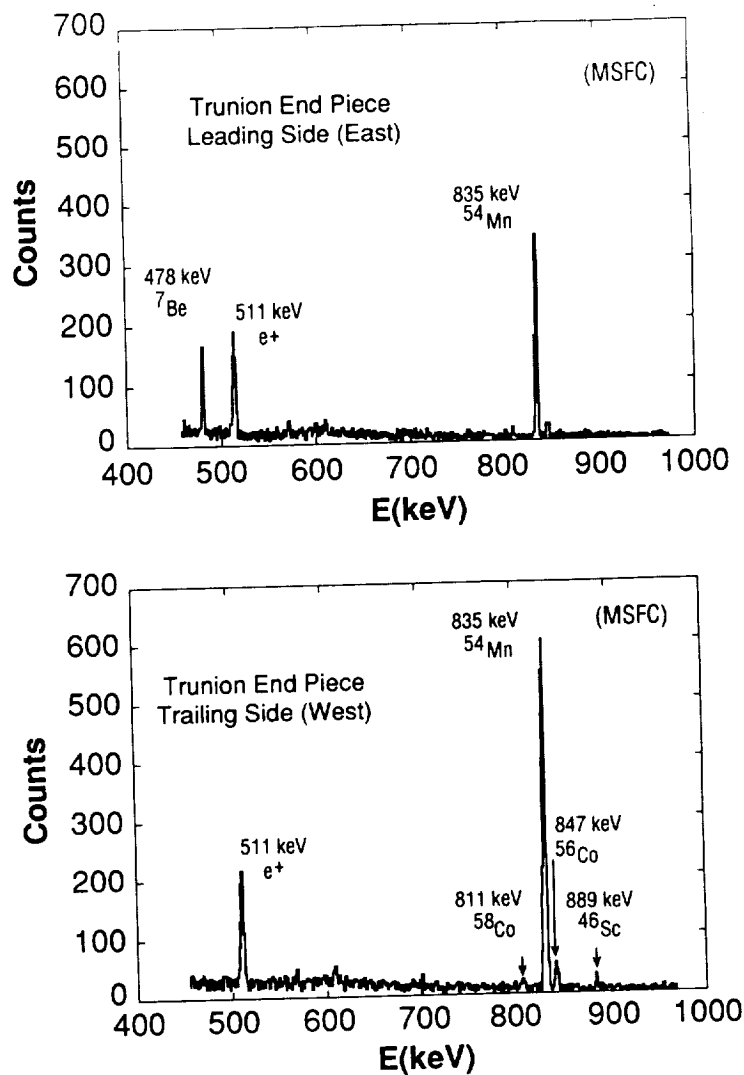


Figure 5. An example of the high resolution gamma ray spectra obtained. These spectra are from twelve hour counts of the end slices (1 cm thick) of two stainless steel trunions, from the leading and trailing sides of LDEF. The east-west effect is clearly seen in the Mn, Co, and Sc lines. The ${}^7\text{Be}$ line is strong on the east (leading) side and is absent on the trailing side. The 511 keV line (positron annihilation) is an artifact of the laboratory spectrum from cosmic rays (from ref. 14,15).

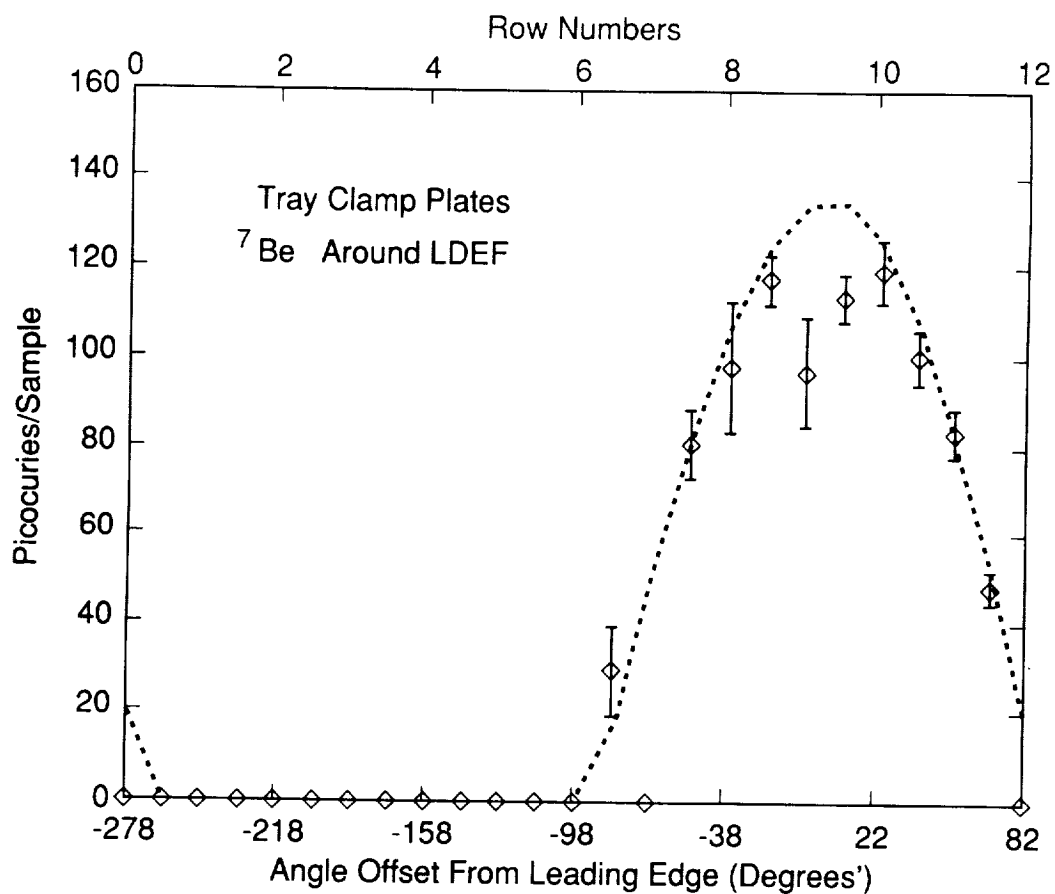


Figure 6. The ^7Be gamma ray line from aluminum experiment tray clamps, taken from each row around LDEF, and counted for 24 hours (each clamp) (from ref. 28).